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Ultrafast high strain rate acoustic wave measurements at high static pressure in a diamond anvil cell

M. Armstrong, J. Crowhurst, J. Zaug, E. Reed

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Photonics West 2009

January 25, 2009

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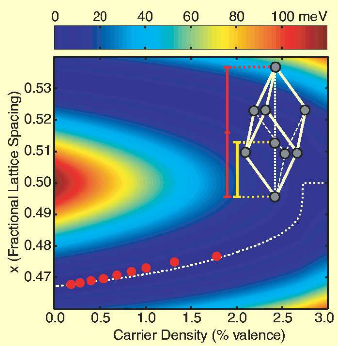
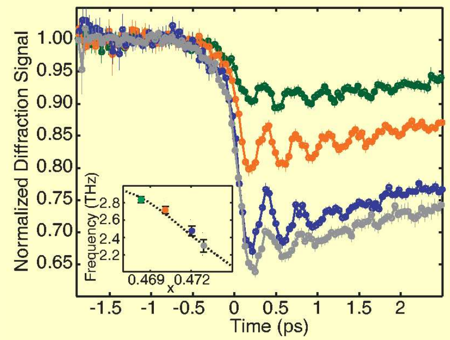
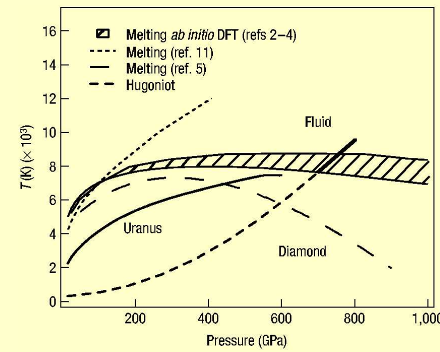
Joseph M. Zaug, Evan J. Reed

Lawrence Livermore National Laboratory

Time resolved methods give access to states that are difficult to achieve using static methods







Ultrafast non-equilibrium phase transitions

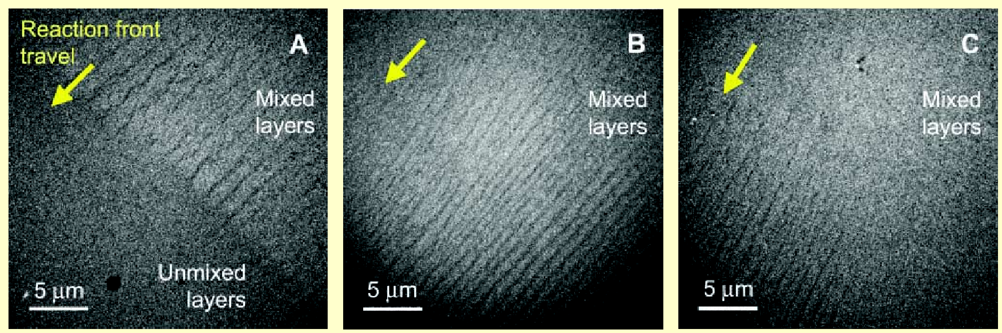
Fritz et al., *Science* **315** (2007) 633

Very high pressure and temperature

Brygoo et al., *Nature. Mat.* **6** (2007) 274

Fast chemical reaction fronts imaged in 2D

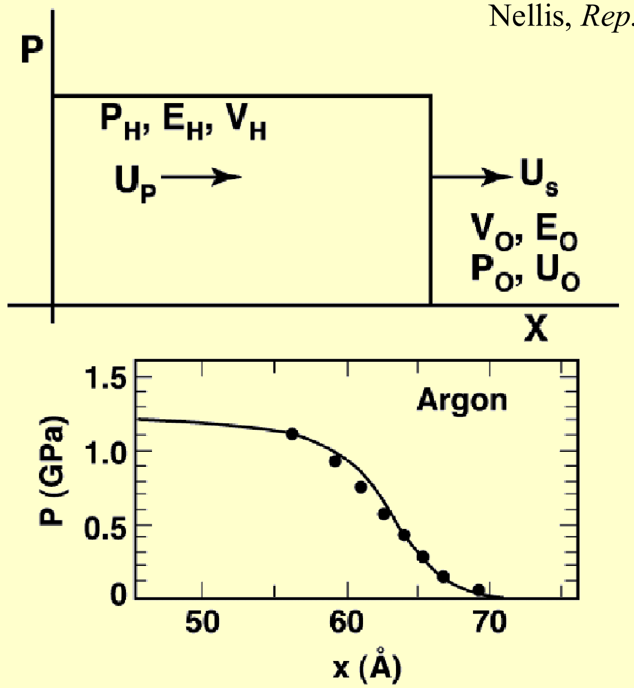
Kim et al., *Science* **321** (2008) 1472



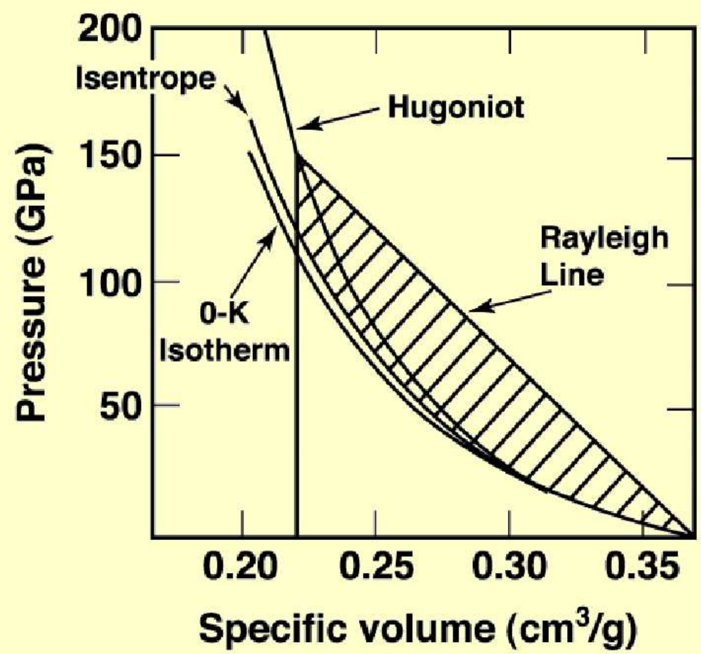
- **Some phenomena only occur on ultrafast (~ps) time scales (e.g. ultrafast phase transitions)**
- **Shock wave experiments provide information about equilibrium states at very extreme pressures**
- **A primary advantage of our technique is that it gives access to transitory states on ultrafast time scales – at the speed of sound, picoseconds equal nanometers**

Shock wave experiments can provide equation of state data for very extreme conditions…

Nellis, *Rep. Prog. Phys.* **69** (2006) 1479



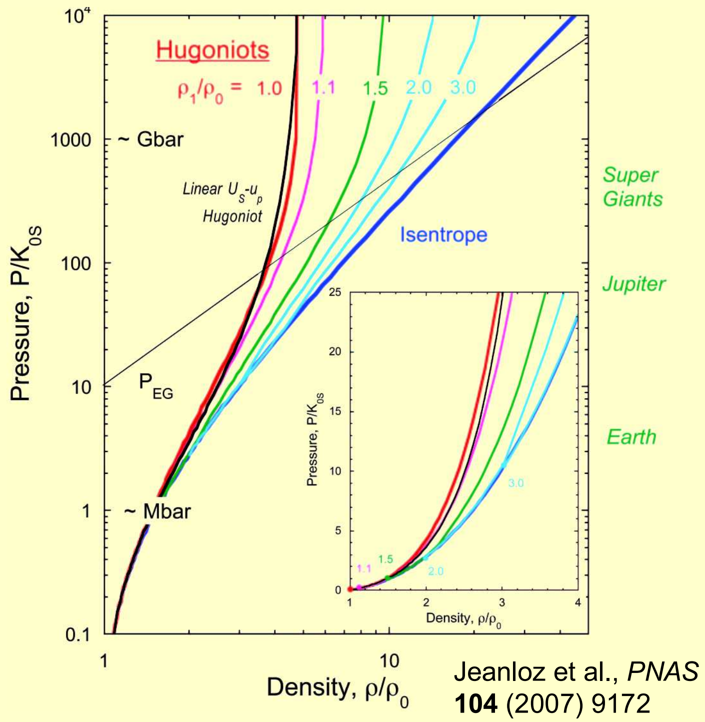
Discontinuous change in pressure



Some Al shock quantities

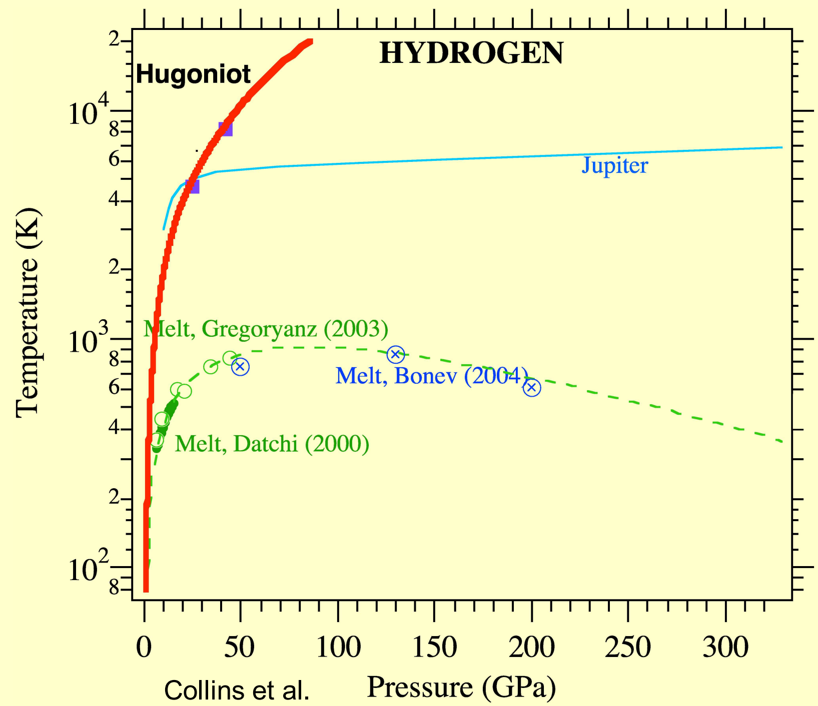
- A shock wave is a discontinuous change in thermodynamic state that propagates faster than the speed of sound in the pre-shocked material
- These are fast, destructive single shot experiments that achieve extreme conditions with data taken over nanosecond to microsecond time scales

But single shock experiments can only access a limited range of thermodynamic states – typically at a higher temperature than obtained with isentropic compression



Jeanloz et al., *PNAS* **104** (2007) 9172

Off-hugoniot, near isentrope EOS

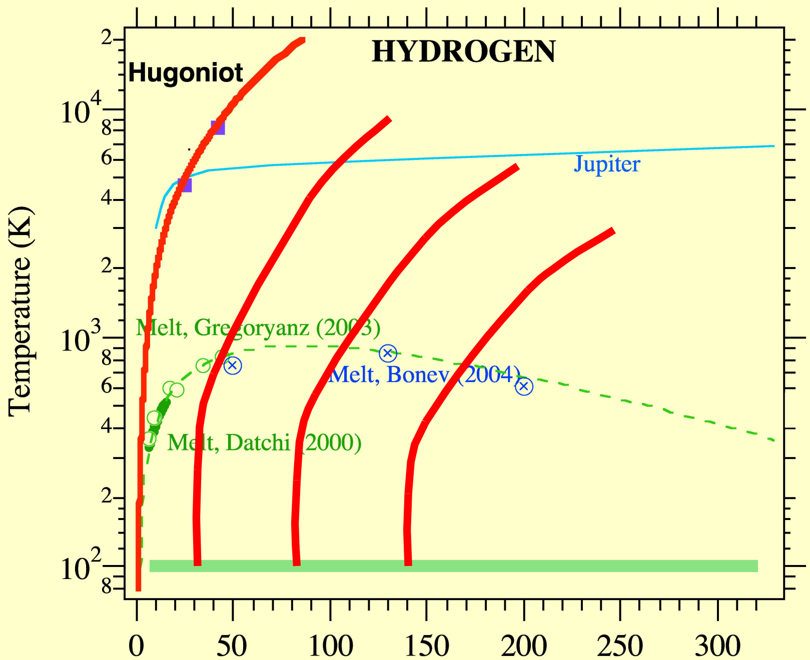


Collins et al.

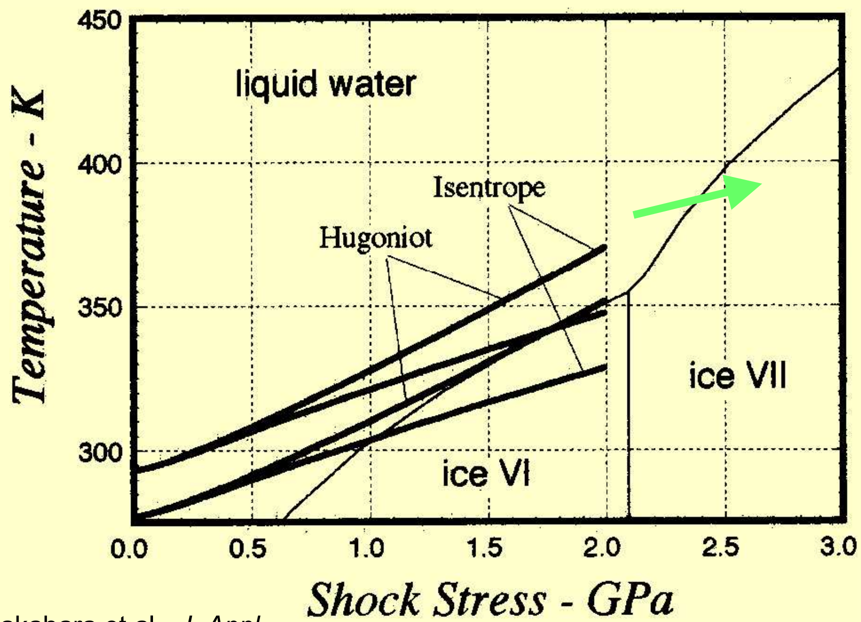
Shock hugoniot of hydrogen

- **Not a significant change for incompressible materials (at pressures we can achieve)**
- **very significant for more compressible materials like hydrogen**
- **Addressed with numerous other schemes including isentropic compression with ramp waves and reverberating shock waves, and with shocked precompressed materials**

Precompression enables more versatile studies through variation of the initial material state



Collins et al.



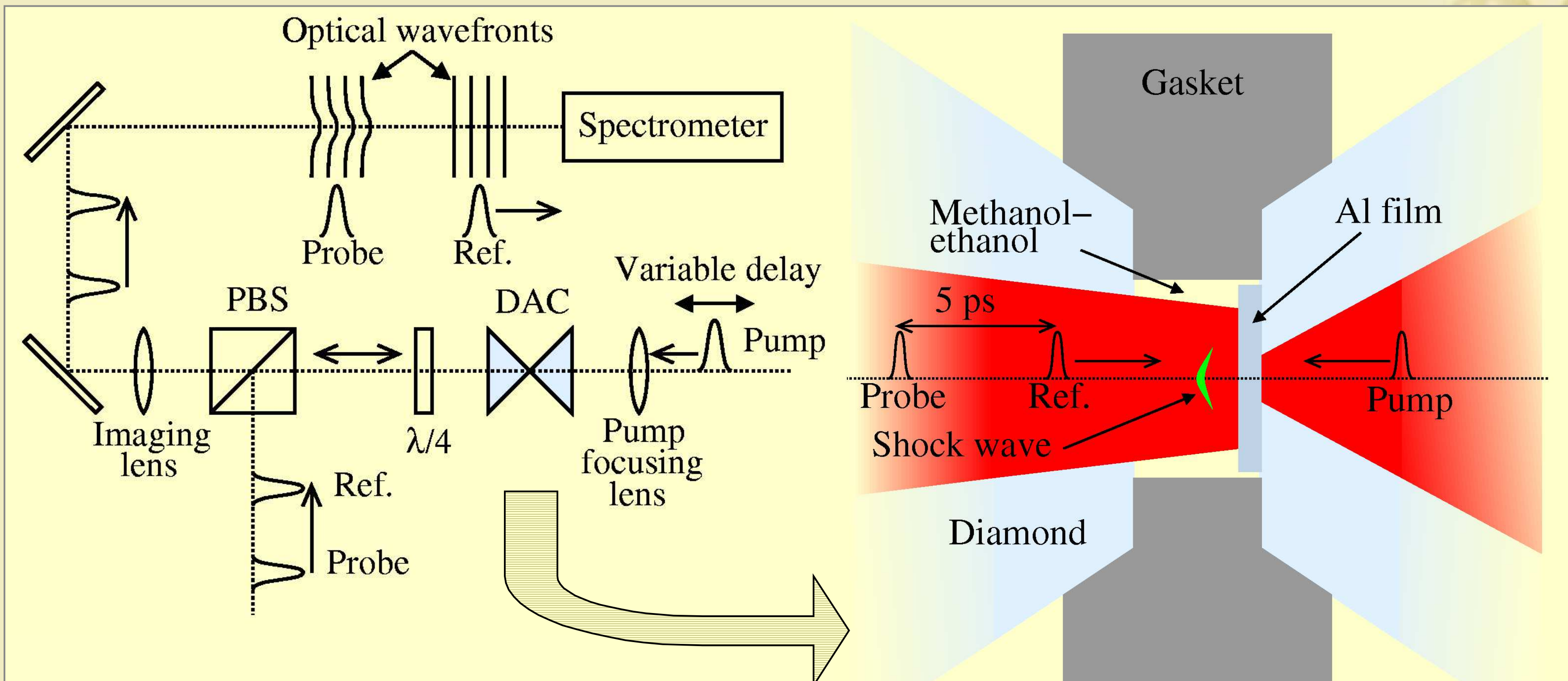
Nakahara et al., *J. Appl. Phys.* **91** (2002) 476

Shock after precompression

Shock near a phase transition

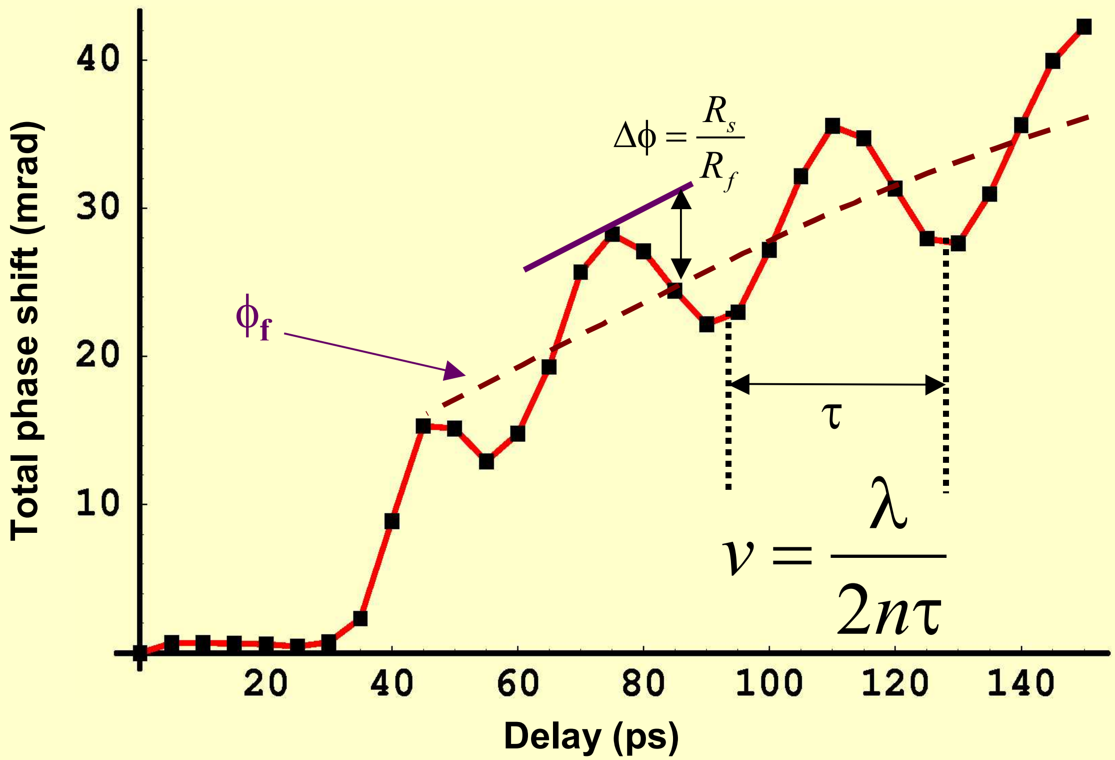
- **Shock dynamics – precompression gives a completely different hugoniot**
- **Phase transitions – tuning the initial state enables "differential" studies**

We probe ultrafast shock induced dynamics using pulsed interferometry



- •Pump initiates an ultrafast shock which propagates through a metal layer and is injected into the pressure medium
- •No need for direct optical excitation (i.e. transparent pressure medium)
- •Access to longitudinal material properties by time of flight measurements
- •Well known technique (e.g. Gahagan et al., *PRL* 85 (2000) 3205), but here in a standard DAC at high pressure

Film motion and the acoustic front contribute to the measured phase shift



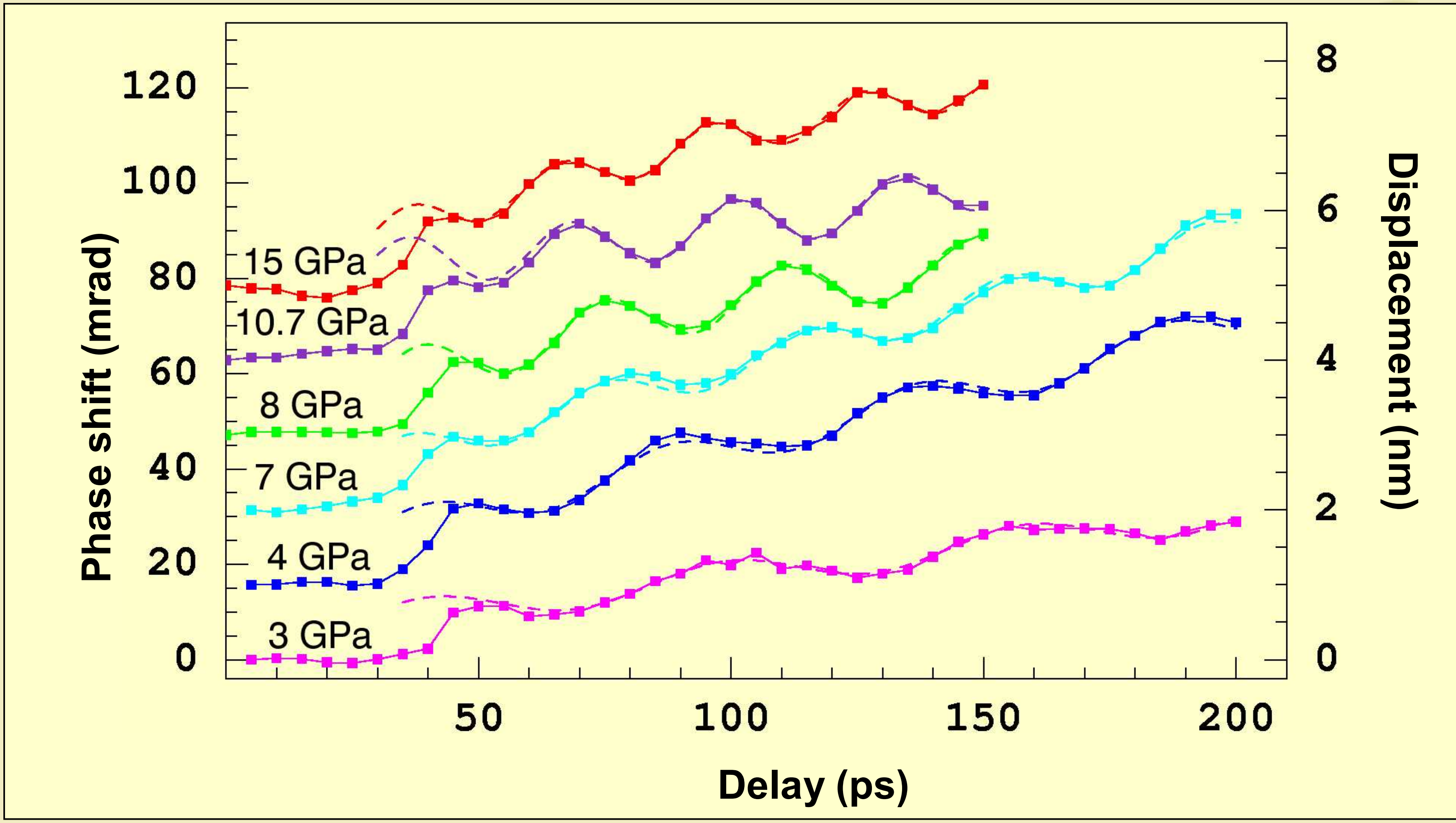
For a given pump-probe delay, the measured phase shift gives a finite derivative (over 5 ps), which is integrated to give the total phase shift. The integrated phase shift can be separated into two contributions: a component associated with the film and an oscillatory component associated with the scanning etalon formed by the Al film and the shock wave

$$\phi_{total} = \phi_f - \frac{R_s}{R_f}\sin\left|\phi_f - \phi_s\right|$$

$$\Delta n \sim 2n\, R_f\, \Delta\phi$$

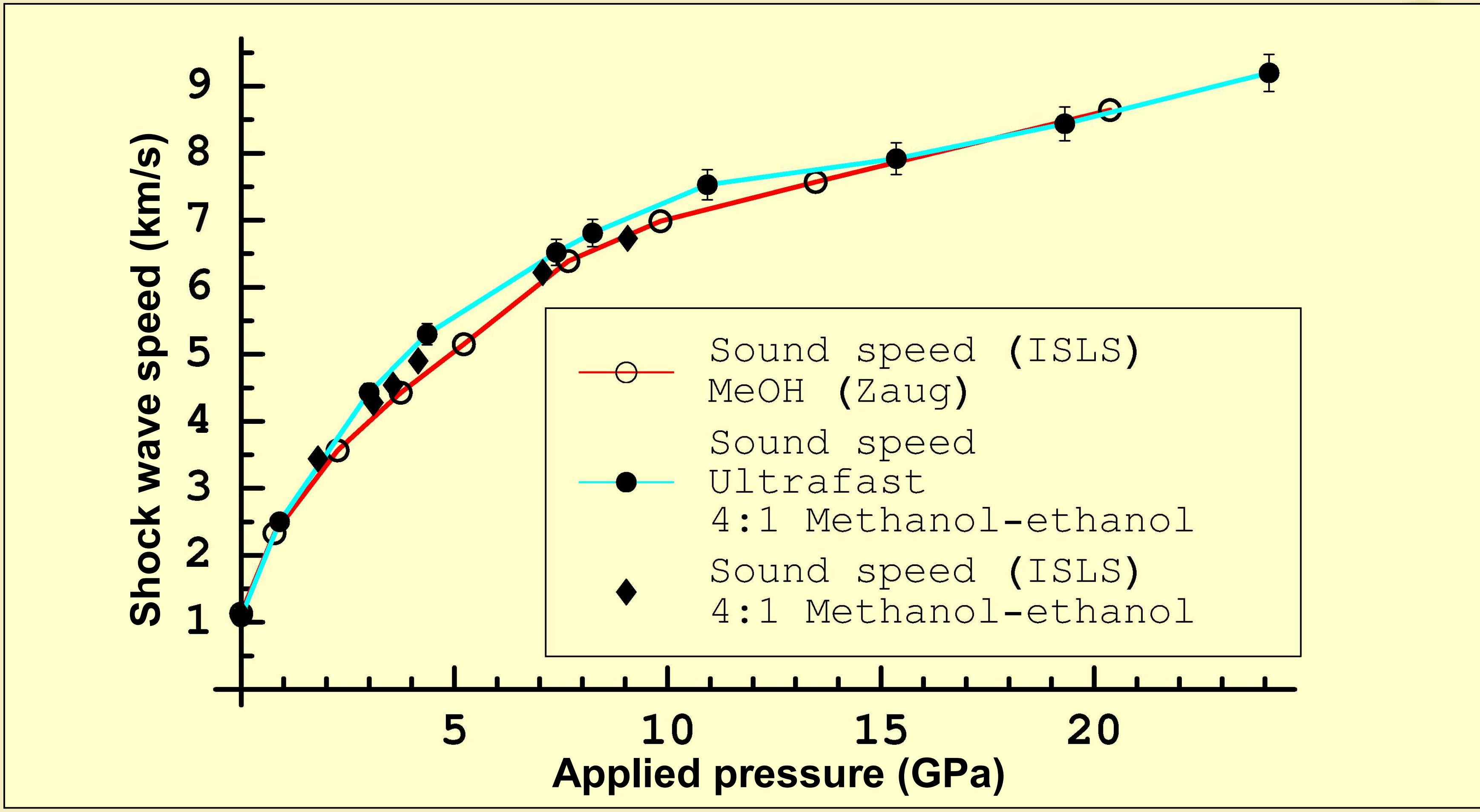
The period of the oscillation gives the shock velocity and the amplitude of the oscillation gives the refractive index change

The data fit a sinusoidal oscillation nicely



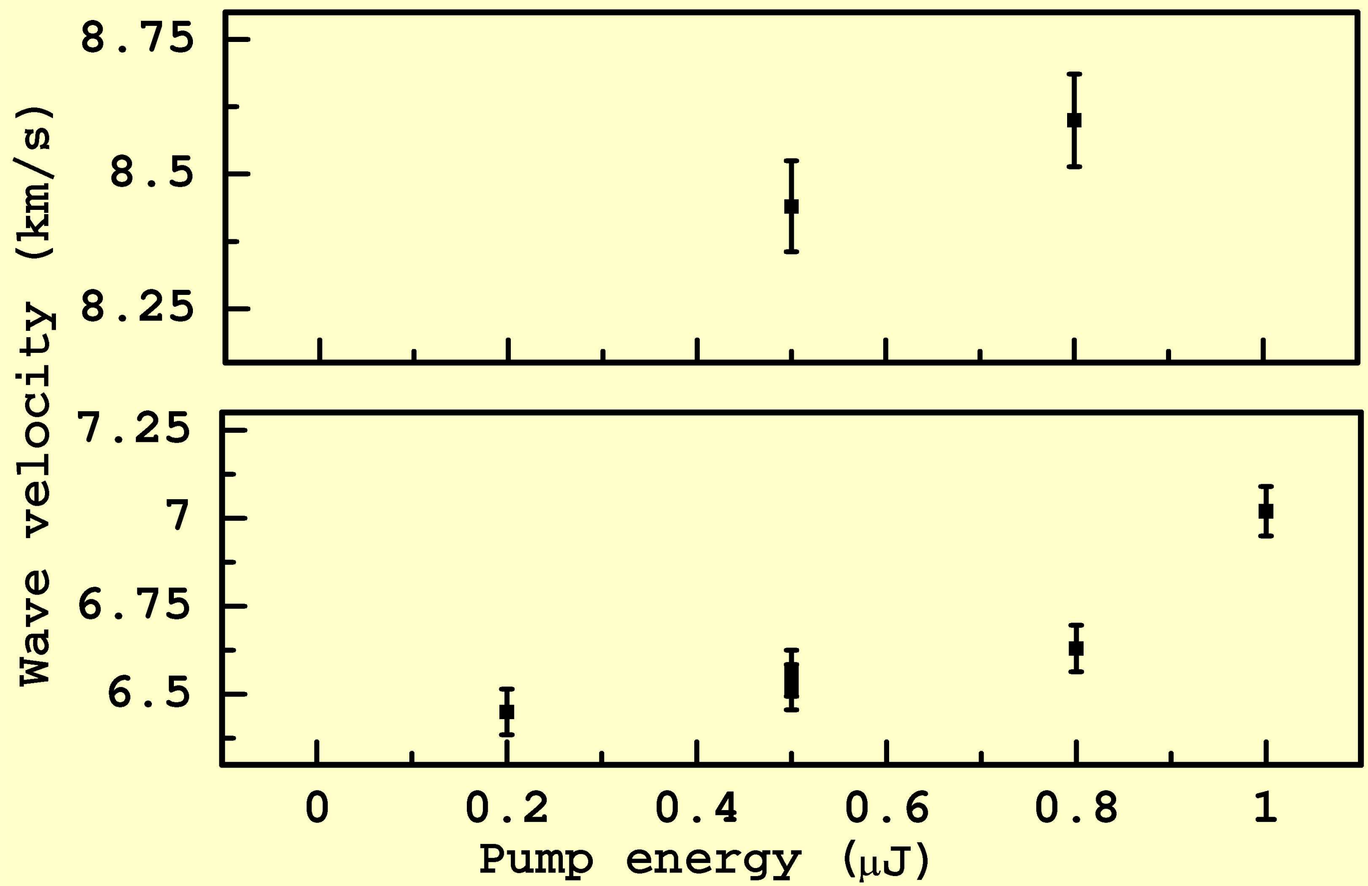
The amplitude of the phase oscillations implies an index difference of about 2-3x10^{-2}. Assuming the static index of refraction, this implies a transient pressure around 2-3 GPa in the medium (APL 92 (2008)).

We have obtained data up to static pressures < 25 GPa



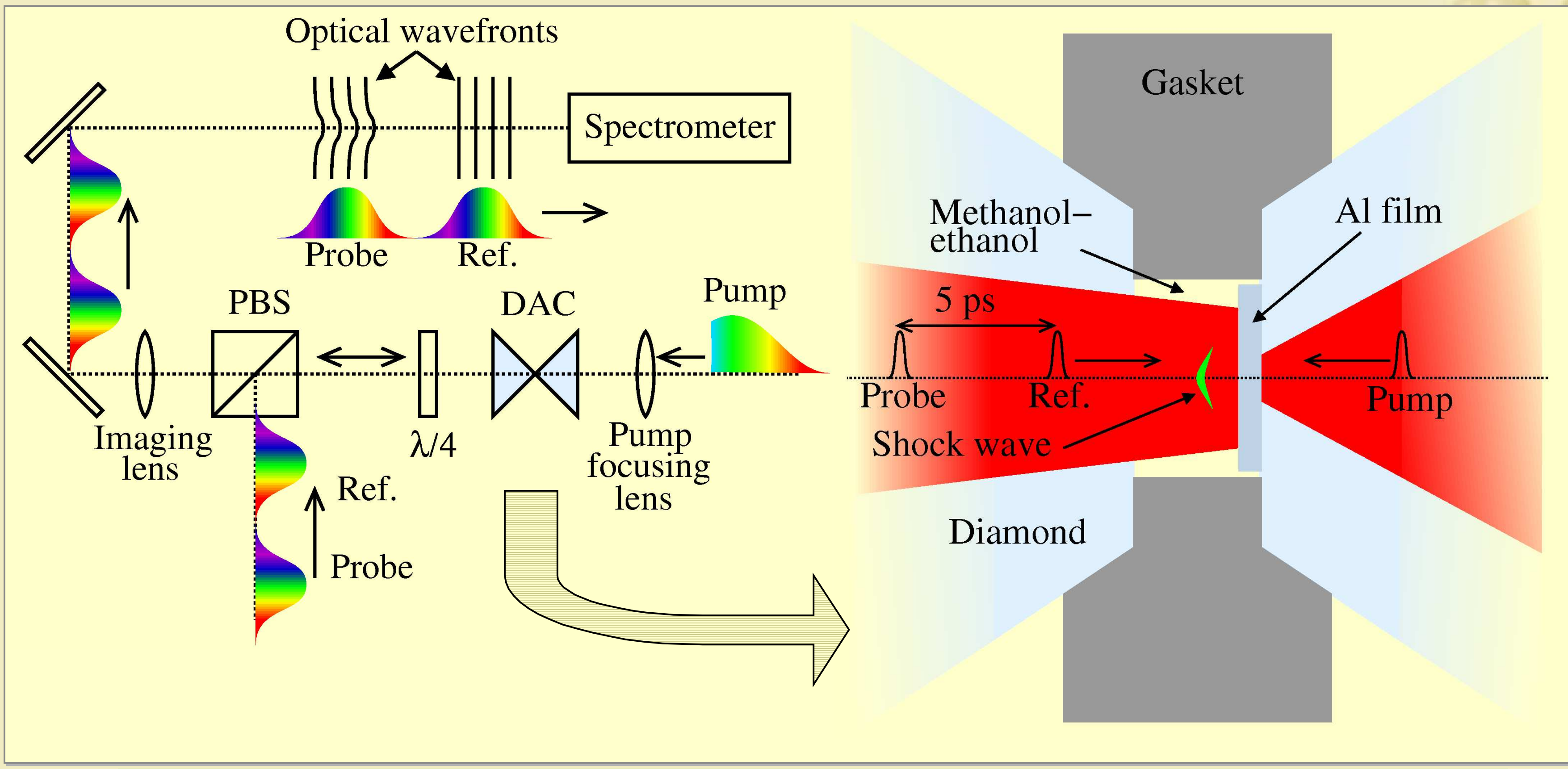
There is a significant deviation from low strain, low frequency speed of sound data at intermediate pressures

We also observe a significant variation of speed as a function of pump energy



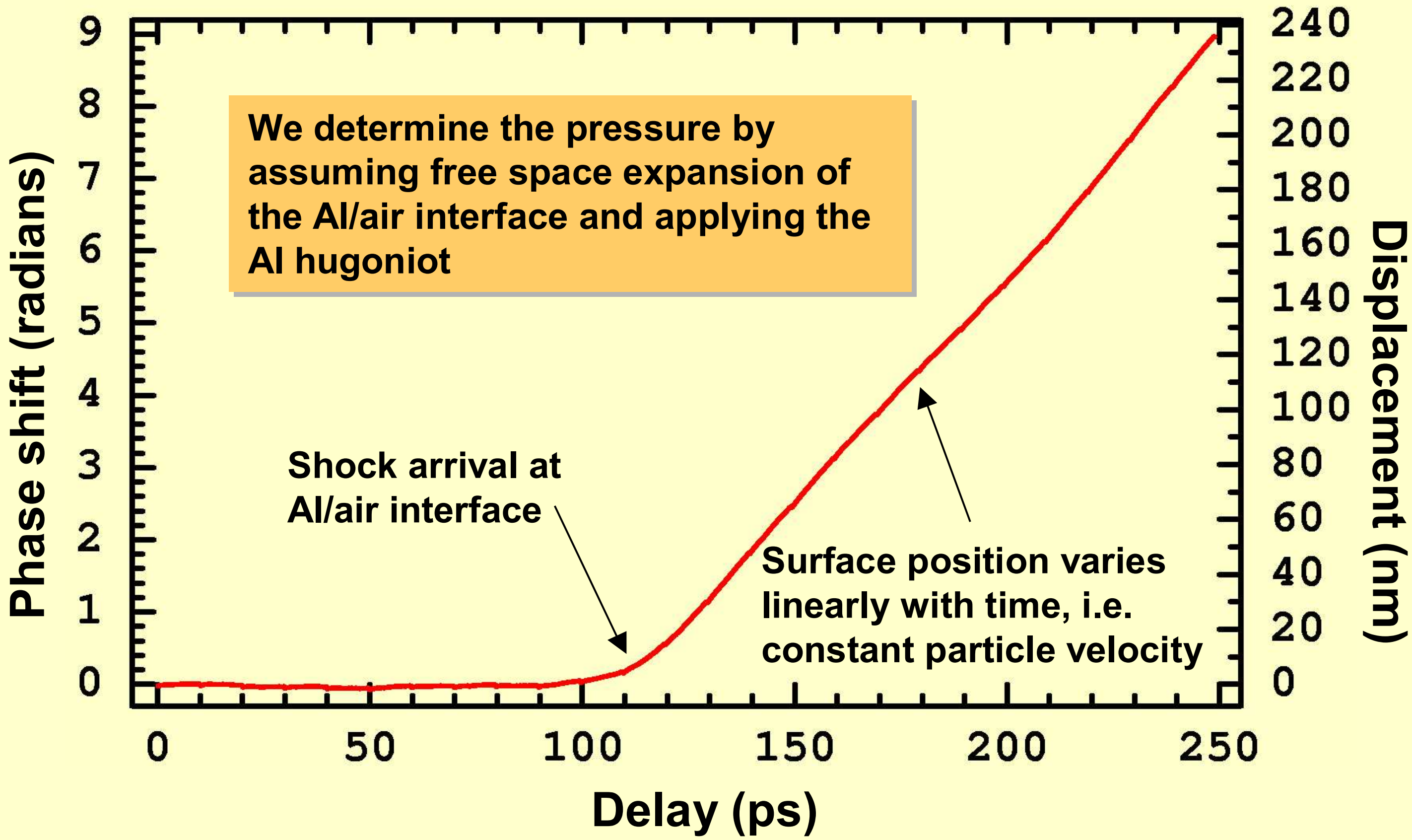
The discrepancy between the sound speed and our measurement is probably a combination of the material response at high frequency (~100 GHz) and nonlinearity at high strain

Chirped pulses allow us to apply a sustained pump to the sample and simultaneously acquire



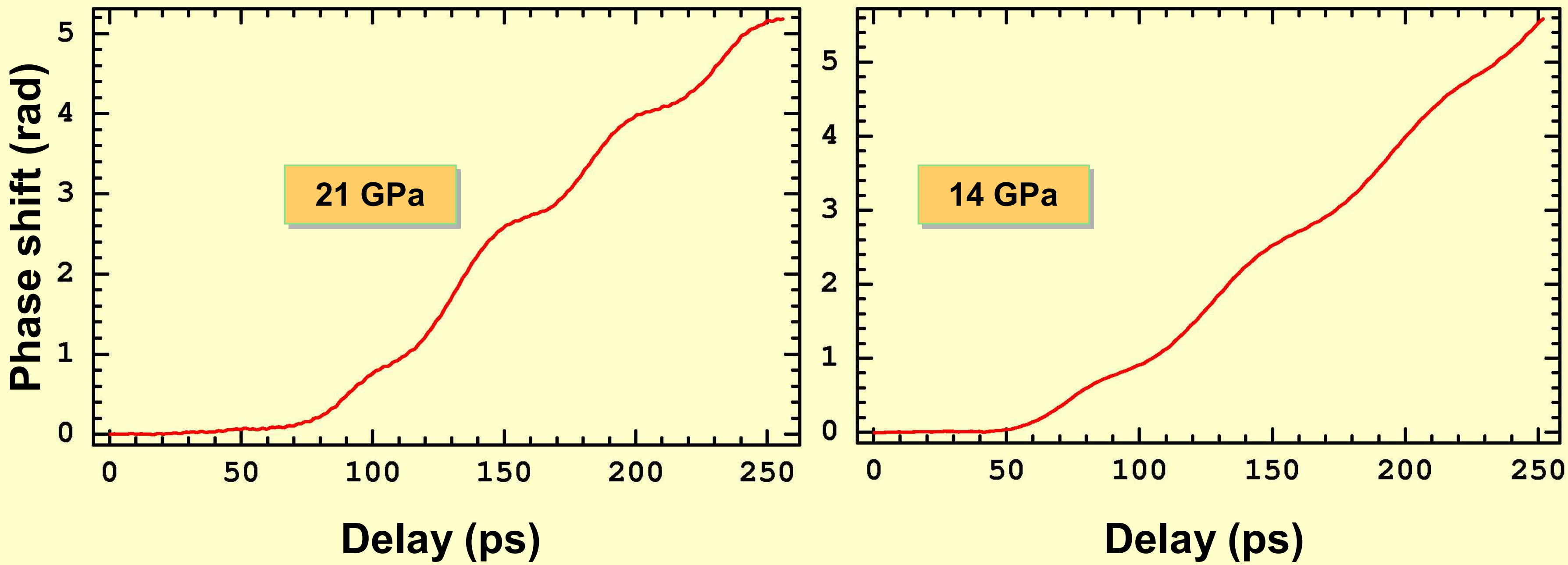
- Allow ablative, single shot excitation
- >300 ps acquisition window with 2-3 ps time resolution
- Data equivalent to multiple shot technique for an irreversible process

Single shot observation of shock waves in 1 μm aluminum on glass



Based on comparisons with data from LANL and Evans et al. (PRL 77 (1996) 3359), we can reach shock pressures under these conditions (outside the DAC) >45 GPa in Al

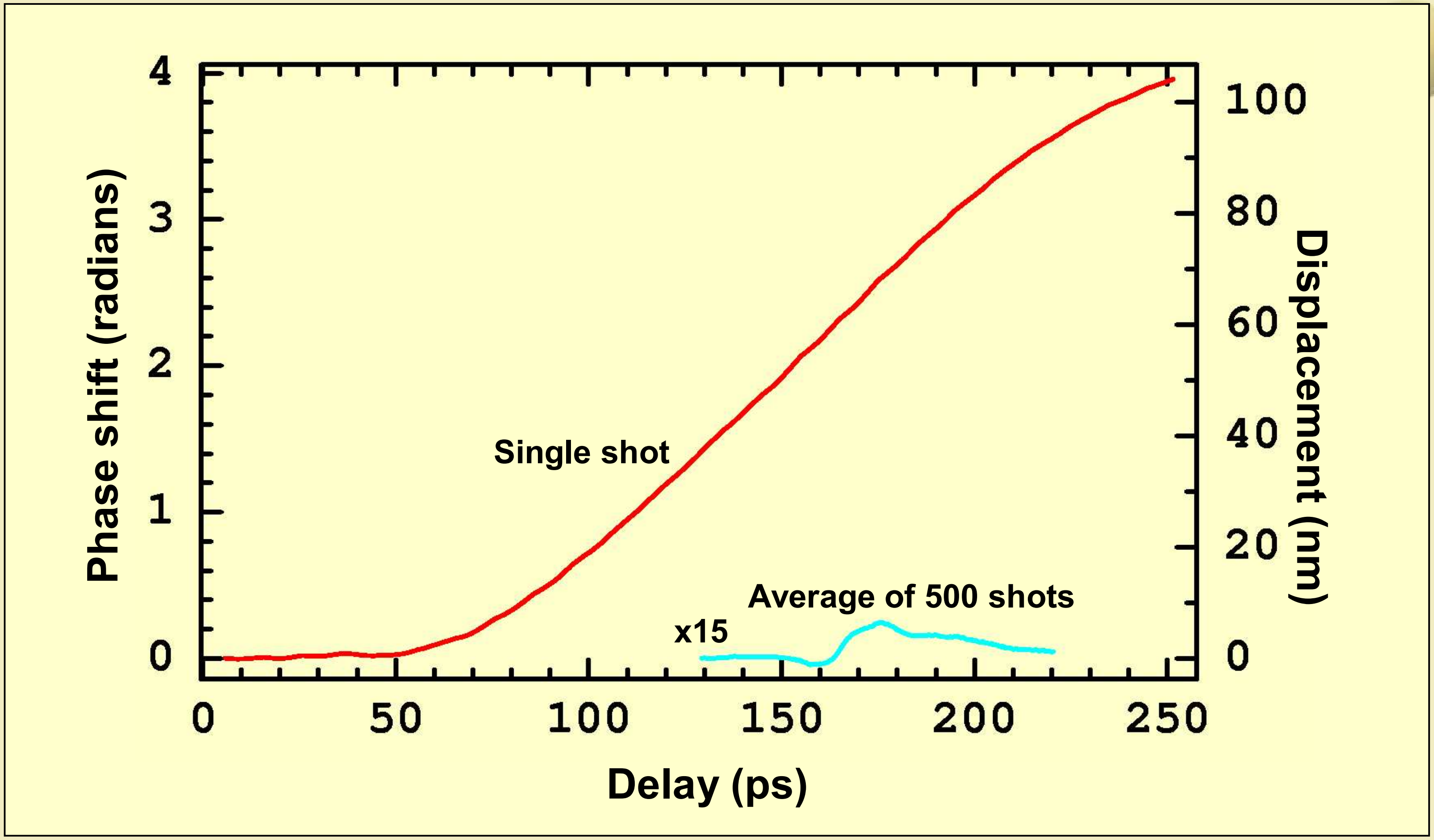
Single shot observation of shocked nitromethane



We can obtain the index of refraction change at the shock front, the shock velocity, particle velocity and pressure increase. The calculated shock and particle velocity give the correct hugoniot to within 10%

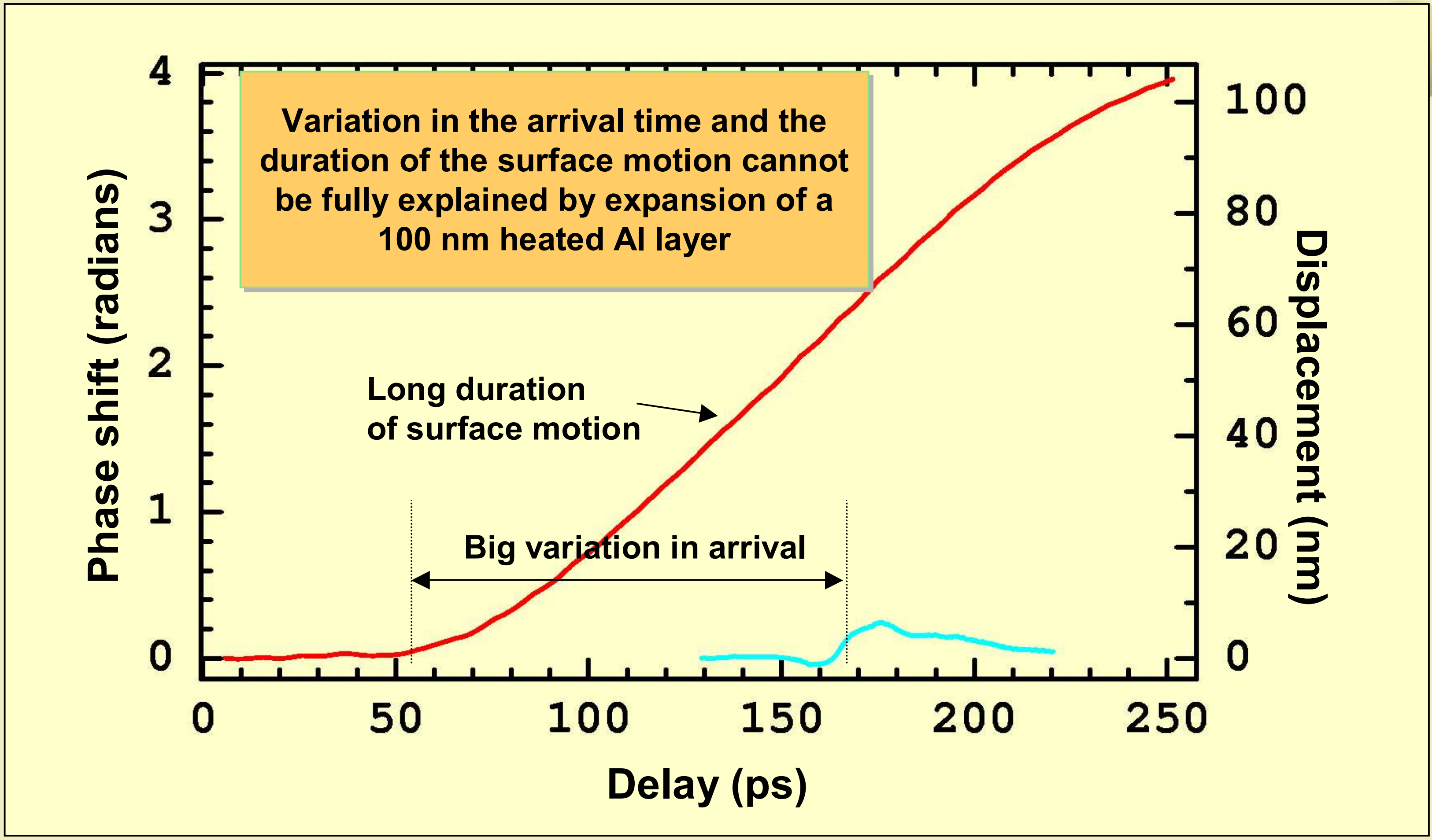
We can reach shock pressures of > 20 GPa in nitromethane (compared to > 50 GPa in Al alone), but we would like to get higher pressure, which may only be possible with precompression

Single shot observation of a shock wave in 1 μm aluminum in a DAC



The sample in this case is a layer of Al directly between two diamonds at ~5-10 GPa precompression – we estimate a shock pressure around 40 GPa

Probably more than just thermal expansion is occurring in the Al



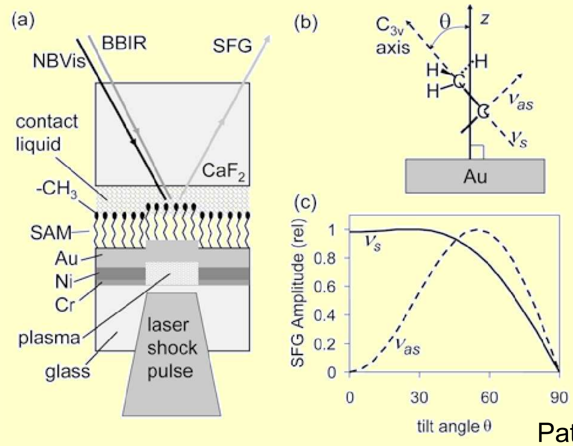
It's likely that we're generating a plasma in the Al. This is a good result – it means we can deliver high intensity light to the ablator.

Summary and future directions

- We have observed shock and acoustic waves under static precompression in a diamond anvil cell
    - Similar observations can be used to shock soft materials and explosives into thermodynamic regimes that are difficult to obtain
    - These techniques have the capability to observe ultrafast phase transformations under shock and acoustic modulation
- Single shot shock pressure up to 40 GPa, with precompression in the 10 GPa range
- Acoustic wave measurements at pressures > 50 GPa
- We are also able to measure transit times through metals at high precompression
- We plan to look at shocking soft materials and examining ultrafast phase transformations next

This work was supported by LLNL LDRD project 06-SI-005 and was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

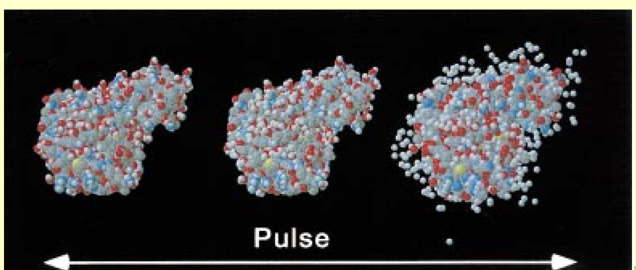
Ultrafast acoustics can be used (and may be necessary) to investigate complex mesoscale dynamics



Molecular chemistry and isomerization on nanometer/ picosecond scales

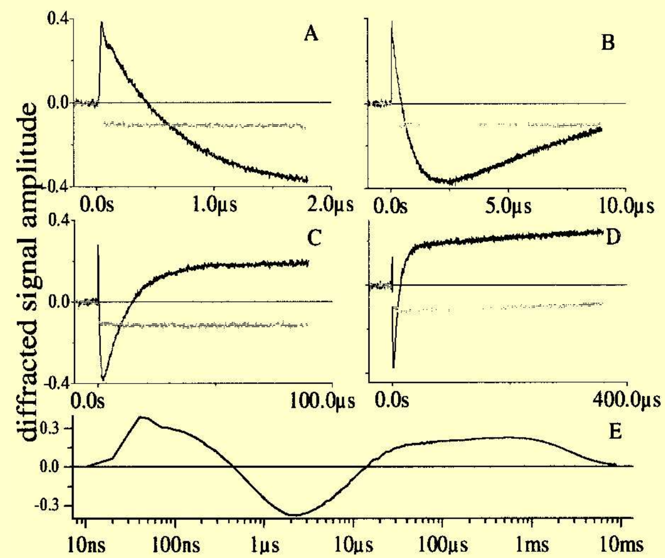
Patterson et al., *PRL* **94** (2007) 663

Neutze et al., *Nature* **406** (2000) 752



Time resolved, "damage free" bioimaging

Stochastic spreading of dynamics



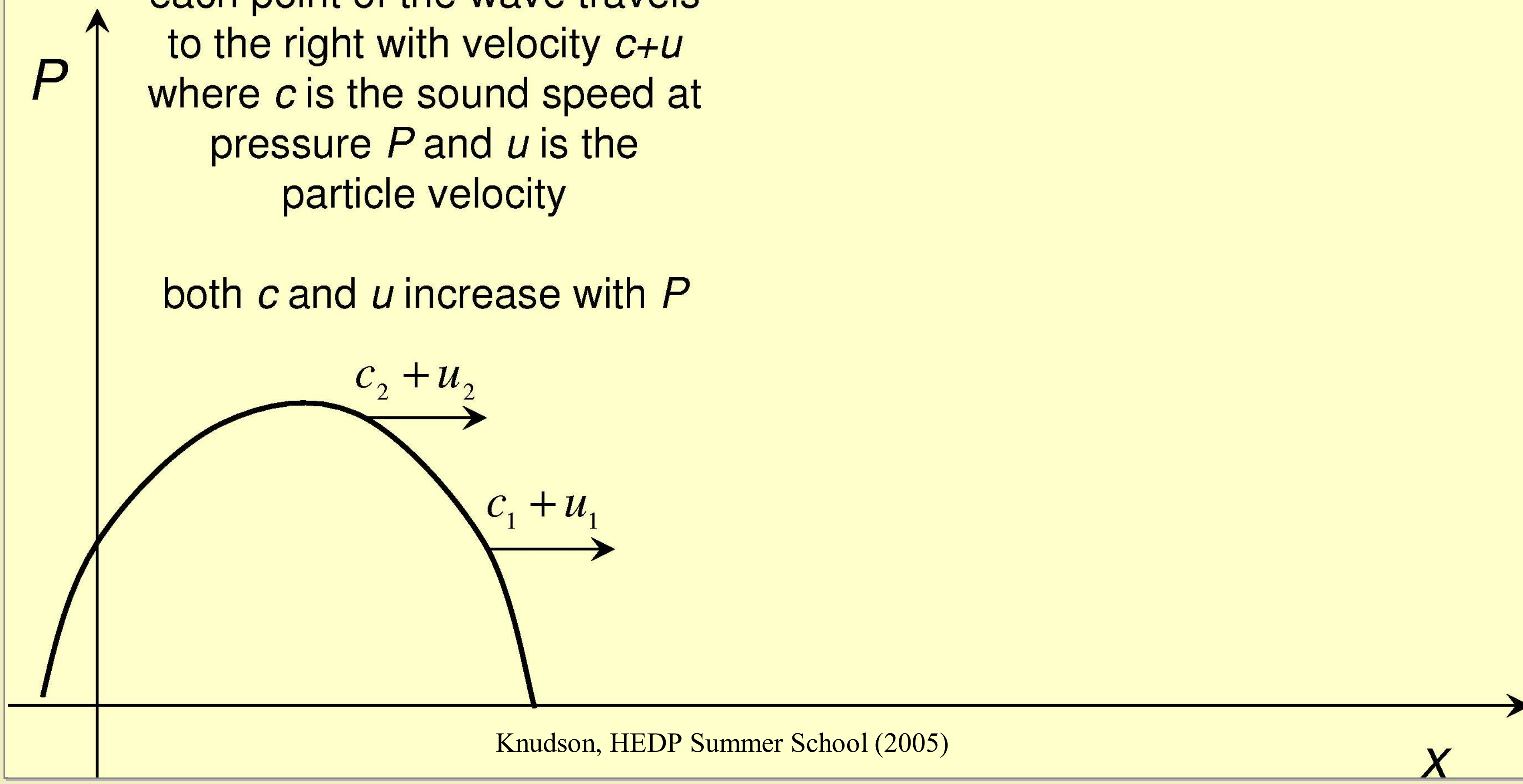
Dadusc et al., *PNAS* **98** (2001) 6110

- **Synchronization – complex phenomena typically include a time smearing stochastic component**
- **Material damage – short wavelength probes deposit a lot of energy in the sample**

What is a shock wave?

each point of the wave travels to the right with velocity *c+u* where *c* is the sound speed at pressure *P* and *u* is the particle velocity

both *c* and *u* increase with *P*



Knudson, HEDP Summer School (2005)

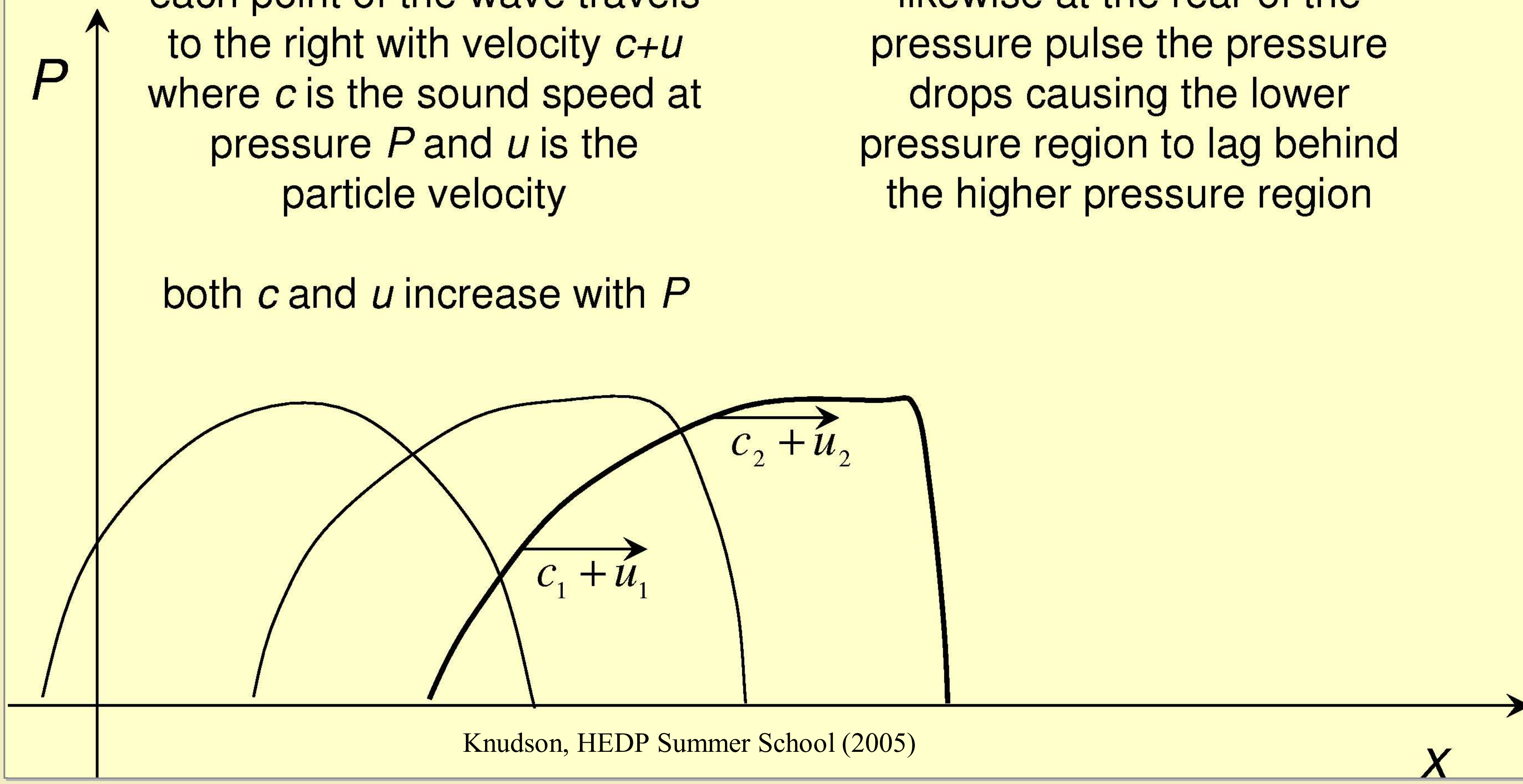
Shock waves form in materials with normal acoustic velocity dispersion – the part of the wave at a higher pressure travels at a higher velocity. Ultimately, a discontinuity (shock front) forms where the sound speed in pre-shocked material is lower than the shock velocity and the sound speed in the post-shocked material is larger than shock velocity.

Shock waves form due to acoustic dispersion with pressure

each point of the wave travels to the right with velocity *c+u* where *c* is the sound speed at pressure *P* and *u* is the particle velocity

both *c* and *u* increase with *P*

likewise at the rear of the pressure pulse the pressure drops causing the lower pressure region to lag behind the higher pressure region



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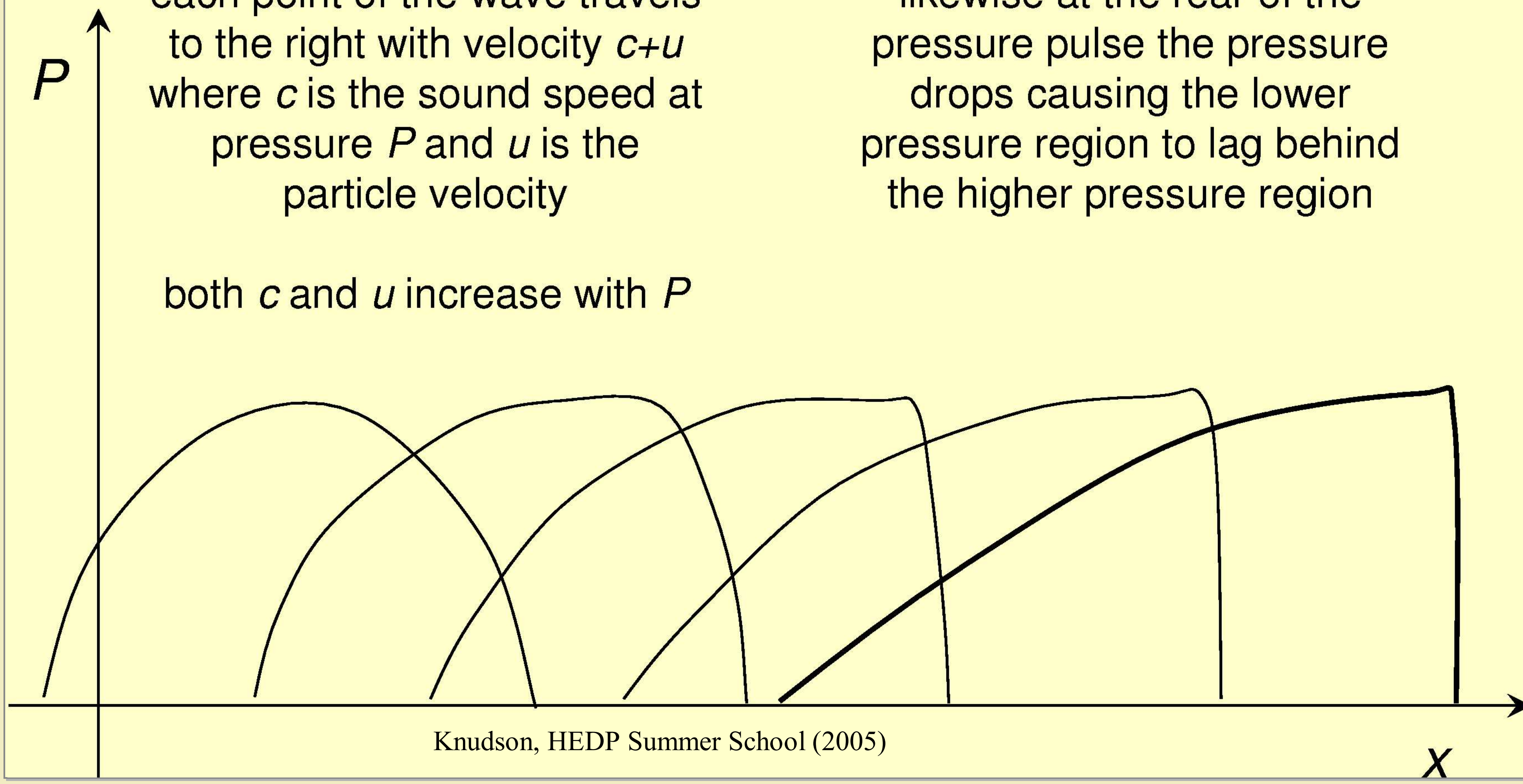

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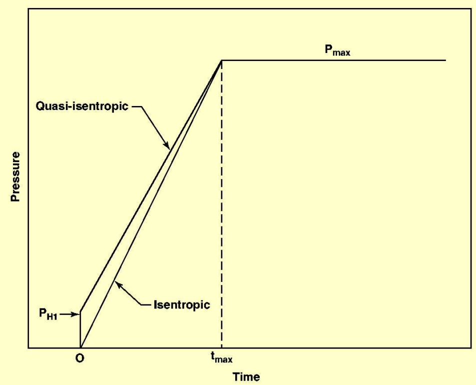
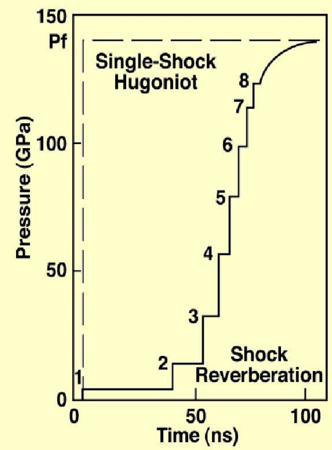
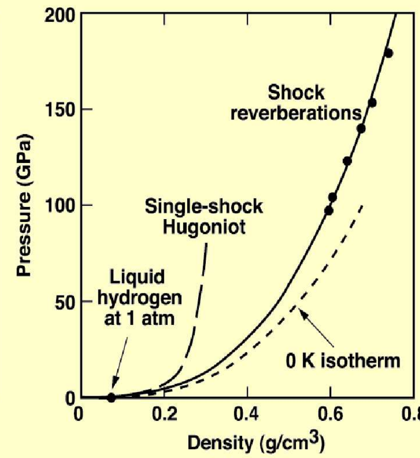
Isentropic compression with ramp waves and shocked precompressed materials are hot topics

Ramp compression

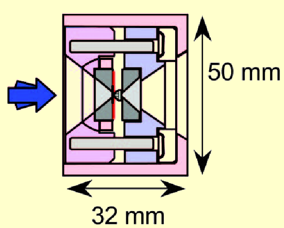


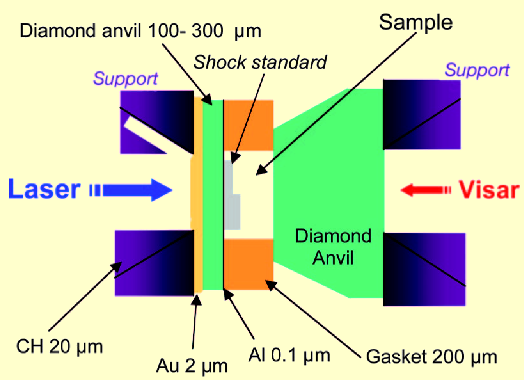




Multiply shocked via reverberation

Nellis, *Rep. Prog. Phys.* **69** (2006) 1479



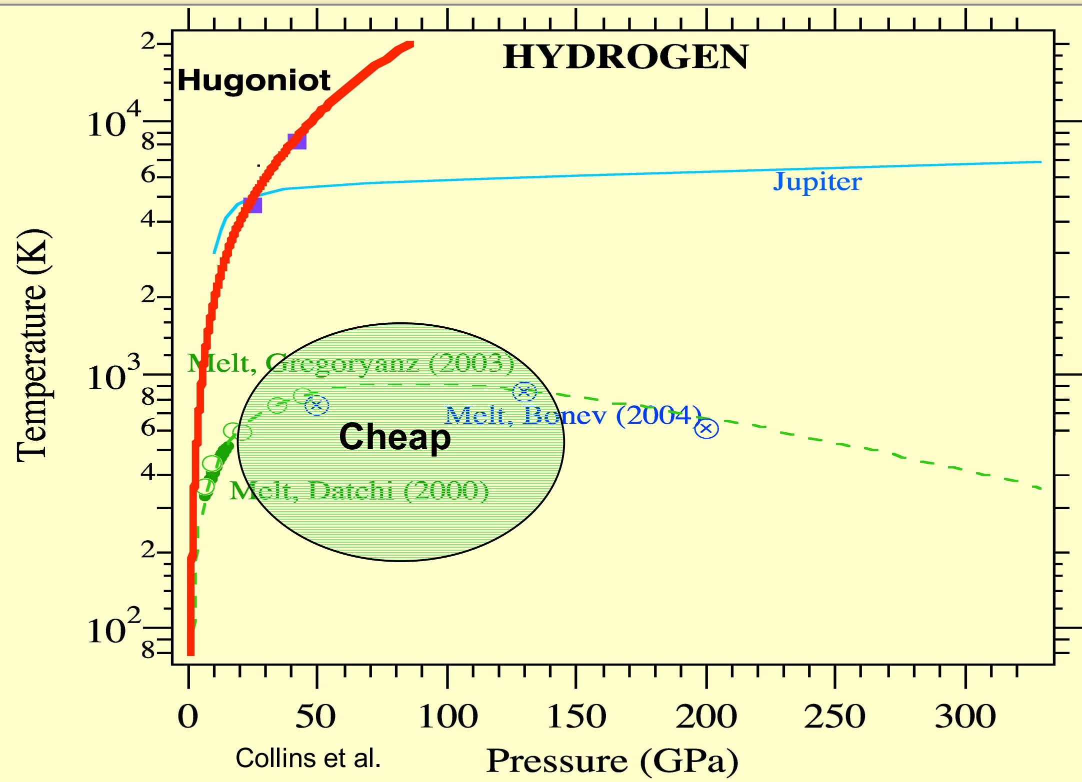


Shocked from a precompressed initial state

Jeanloz et al., *PNAS* **104** (2007) 9172

These experiments provide data about thermodynamic states more similar to planetary interiors than single shock experiments from low pressure

Where do we fit in?



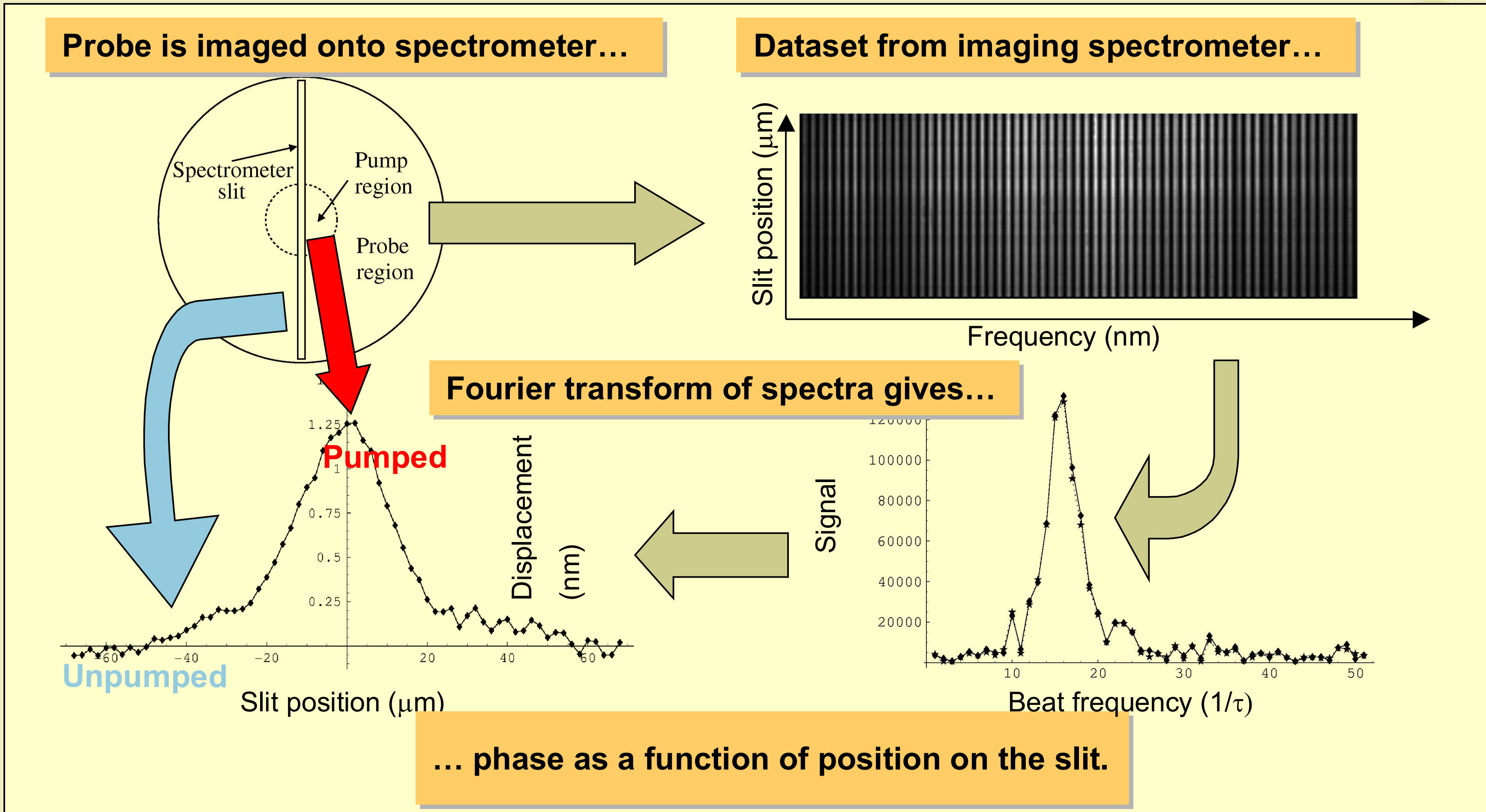
Collins et al.

The shock and diamond anvil cell communities are well established

Our unique capability is the generation and detection of 10s GPa shock waves (and low pressure acoustic waves) in materials under precompression of 10s GPa

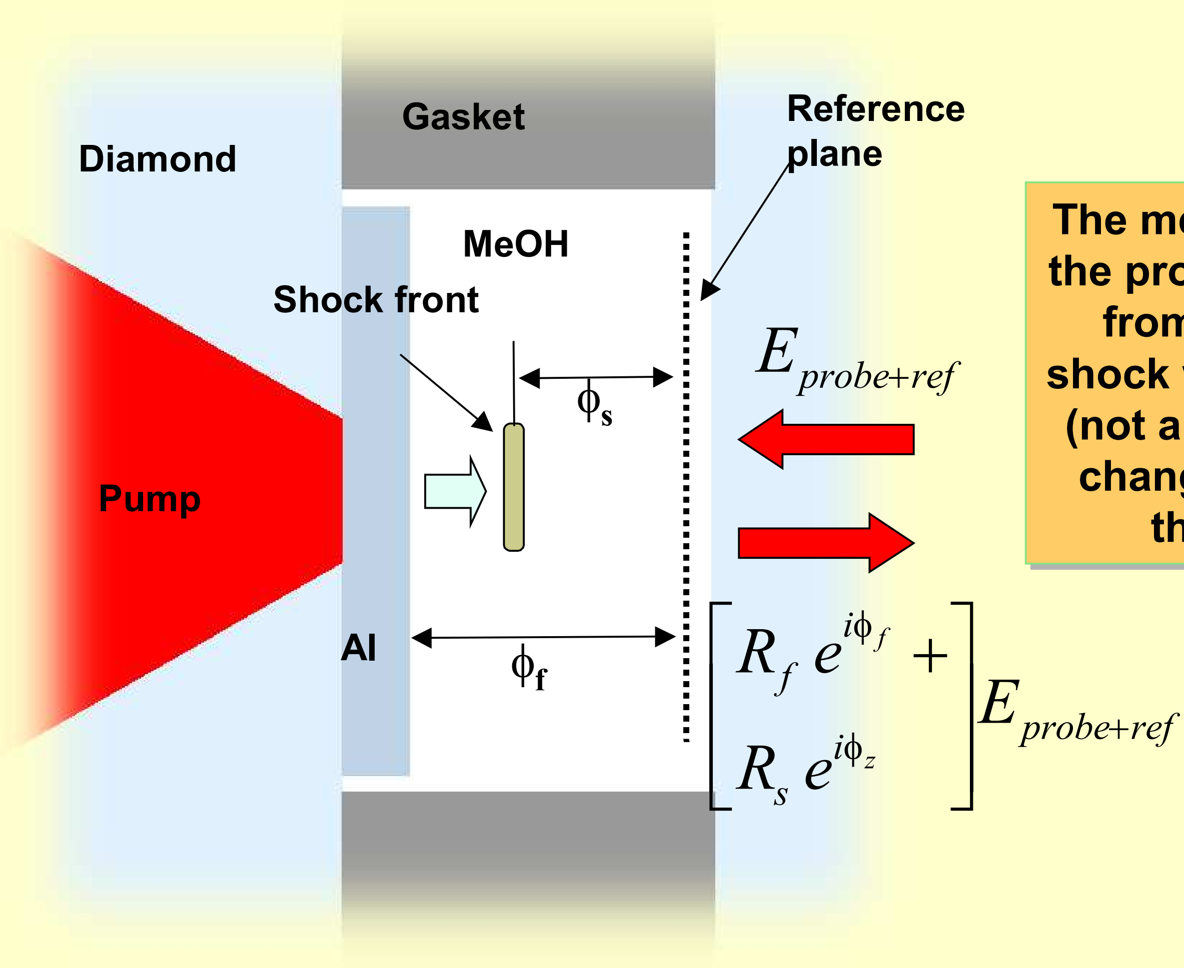
- **Ultrafast material dynamics and chemistry under a much wider range of initial conditions**
- **Detonation chemistry of explosives that cannot be achieved any other way (LLNL's interest)**
- **A 1 person, table top experiment –appropriate for intermediate scale experiments in the Mbar regime**

Ultrafast interferometry is a very sensitive technique



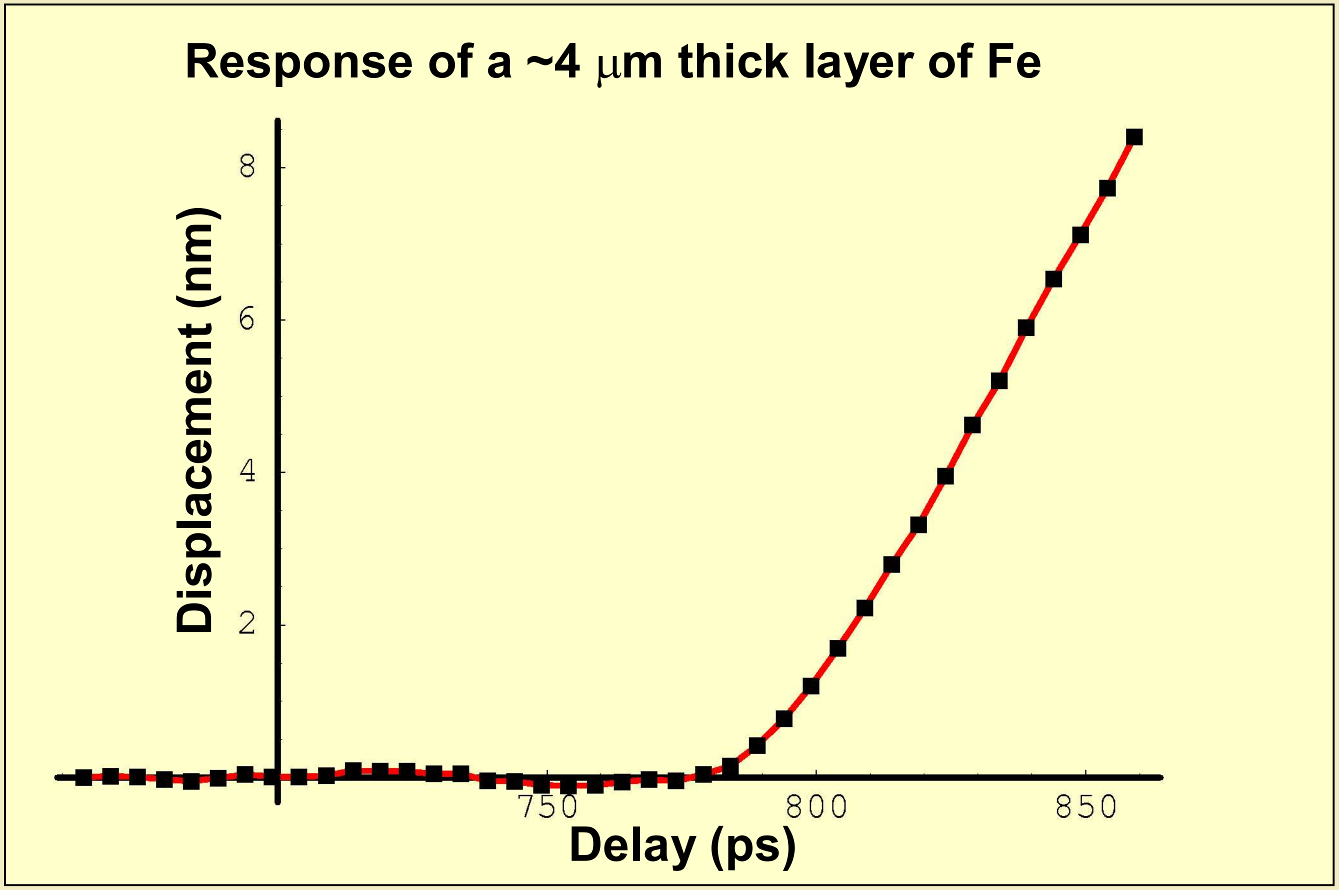
Typically, phase shifts equivalent to <1 nm of surface displacement can be detected in a single shot.

There is a simple model for the measured phase



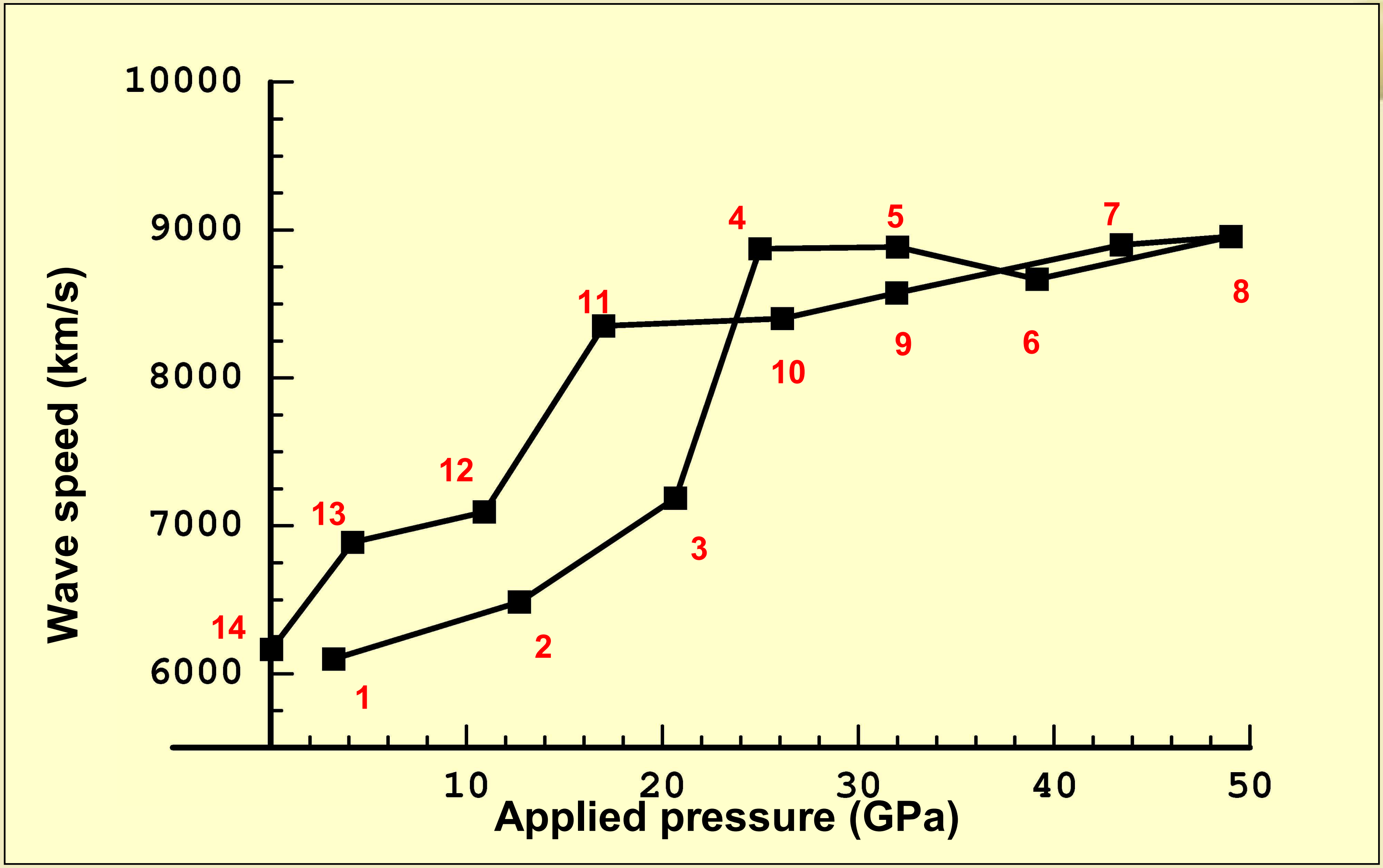
The measured phase results from the probe and reference reflecting from both the Al film and the shock wave. Only the phase shifts (not amplitudes) are assumed to change over the delay between the probe and reference

We observe response through relatively thick layers of metal in a cell capable of very high (>50 GPa) static pressure



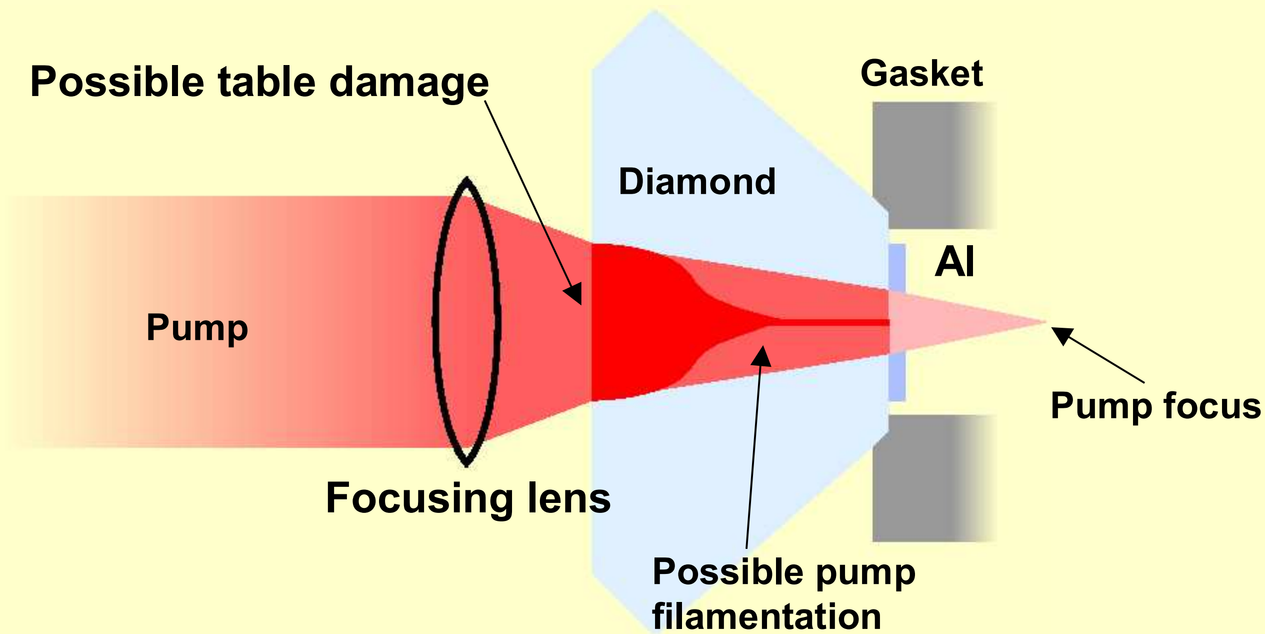
Observation through thicker layers will provide more accurate velocity measurements as well as enabling very high applied pressure

Measurements of sound speed in Fe directly compressed up to 50 GPa



Hysteresis in velocity probably corresponds to lag in phase transformation

Pump nonlinearity, diamond table damage, and self-focusing are significant issues

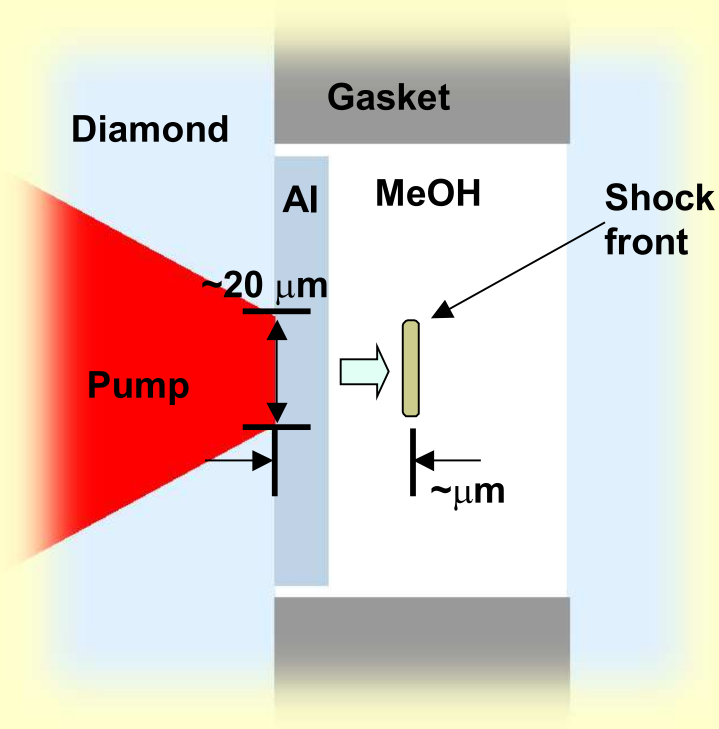


- Long pump duration (800 fs) – reduce peak power to avoid filament formation
- High numerical aperture pump focus – diffraction dominates focusing, avoids table damage
- Focus behind sample – a very tight focus gives too small a pump spot at the focus

Ultrafast experiments have generally smaller scale

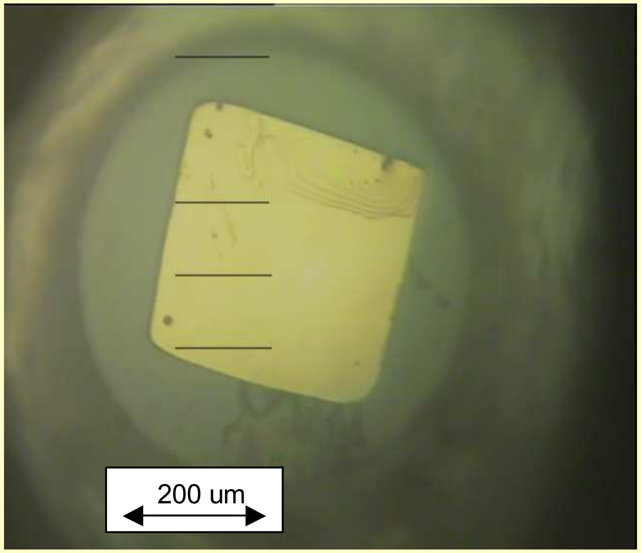
With total propagation distances around 1 μm (corresponding to a total delay < 200 ps), a reasonable aspect ratio can be obtained even with a 20 μm FWHM pump pulse…

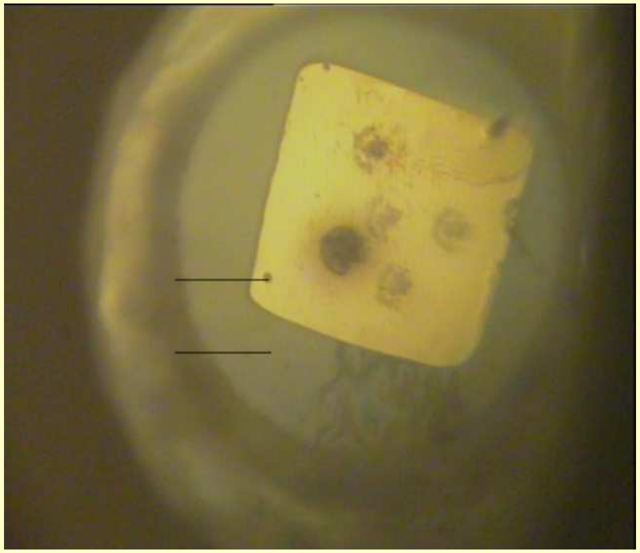
A very small pump spot allows the pump energy to be smaller, mitigating peak power dependent effects like pulse self-focusing, and allowing the use of large numerical aperture focusing, which reduces the chance of damage at the diamond table



- Ultrafast time resolution enables small scale experiments
- Different damage mechanism than ns scale experiments

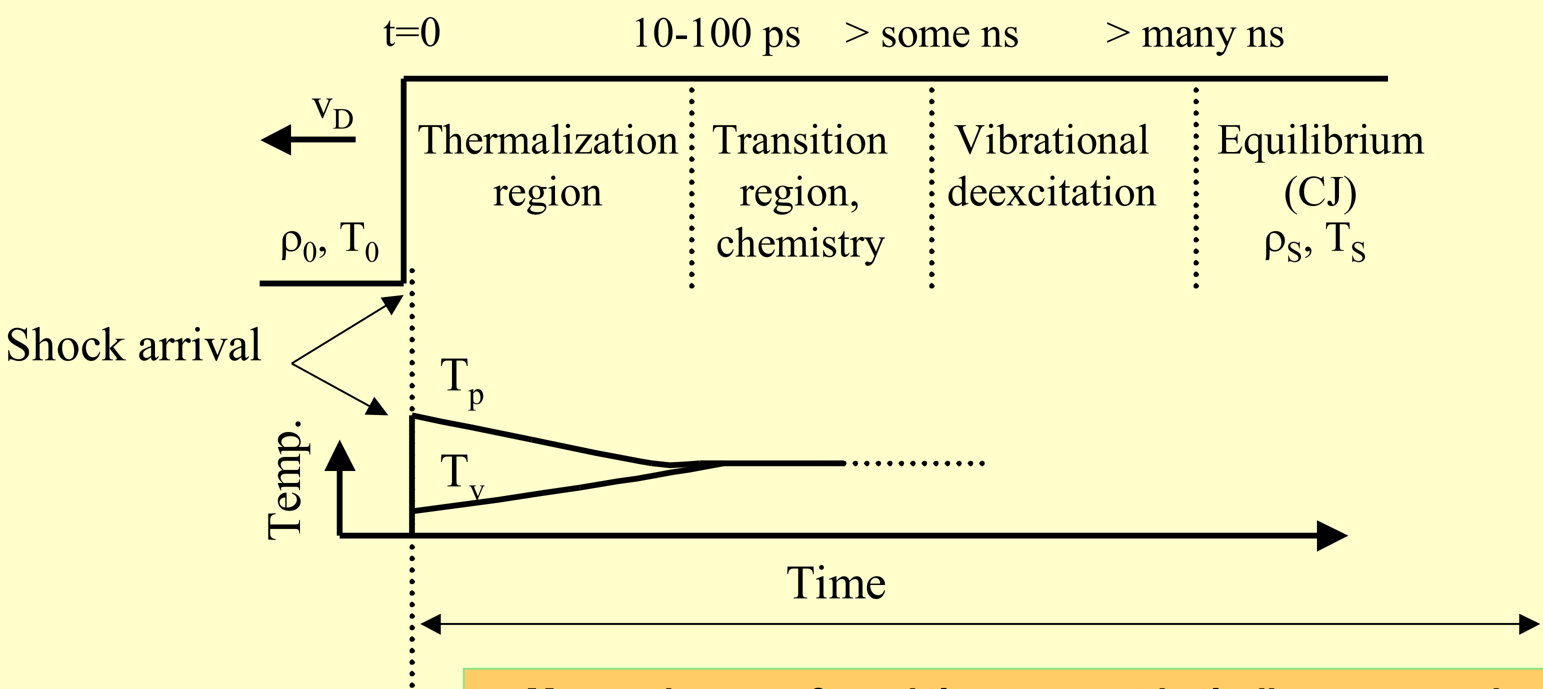
We have demonstrated that we can ablate samples in the DAC with ~ 100 fs pulses





•We were able to ablate gold under high static pressure in both liquid and solid media (argon).
•A conventional DAC was used without any modifications – no additional constraints imposed.
•Technique should work on range of interesting samples possibly with suitable choice of ablator

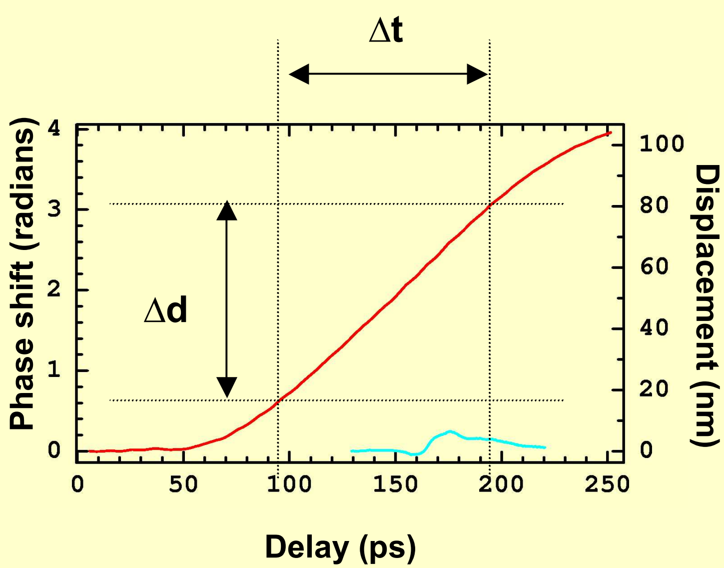
Typical detonation fronts are “thick”



Many microns of spatial extent, not including propagation time to develop a steady state detonation front

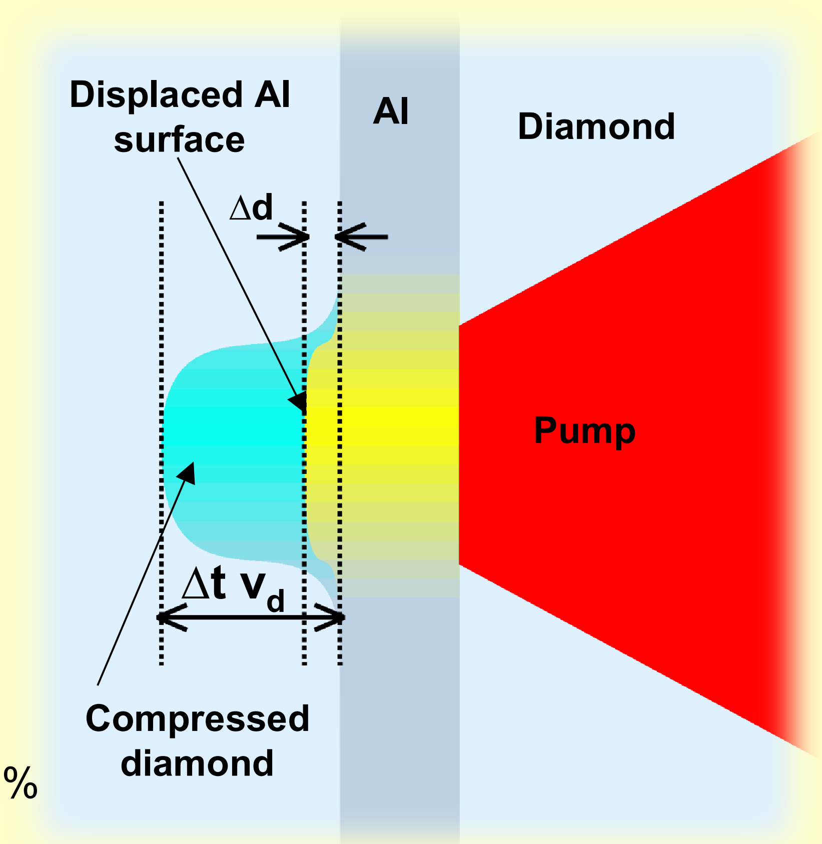
The DAC and ultrafast shocks can be used to investigate differential or overdriven behavior of molecules that detonate, without having to develop a traditional detonation front – ultrafast techniques can give access to the chemical reaction

Diamond may be a convenient material with which to calibrate the pressure



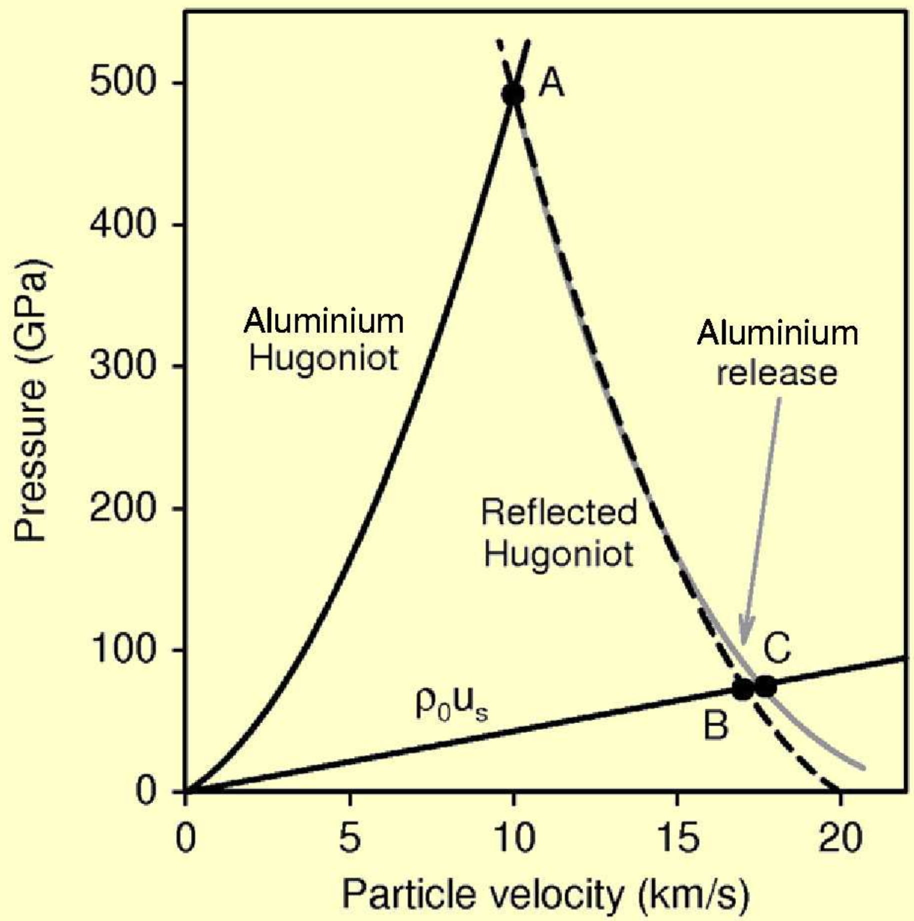
$$strain = \frac{\Delta d}{v_d \ \Delta t} \approx 3.7\%$$

P=strain * elas. con. ~ 1100 GPa * 3.7%
~ 40 GPa



We can measure the strain in the diamond by estimating the compressed volume and measuring the degree of compression

Shock wave excitation of soft materials from low pressure



Nellis, *Rep. Prog. Phys.* **69** (2006) 1479

Precompression starts materials at higher density giving higher pressure injected into the pressure medium